

# **Satellite Synthetic Aperture Radar Detection of Ocean Internal Waves in the South China Sea**

PI: Quanan Zheng

Department of Atmospheric and Oceanic Science, University of Maryland,  
College Park, MD 20742

Tel.: (301) 405-8253 Fax: (301) 314-9482 e-mail: [quanan@atmos.umd.edu](mailto:quanan@atmos.umd.edu)

CO-PI: R. Dwi Susanto

Lamont Doherty Earth Observatory of Columbia University,  
Palisades, NY 10964-8000

Tel.: 845-365-8545 Fax: 845-365-8157 e-mail: [dwi@ldeo.columbia.edu](mailto:dwi@ldeo.columbia.edu)

Grant Number: N00014-05-1-0328

## **LONG-TERM GOALS**

The long-term goal of the project is to meet the goal of ONR DRI NLIW, which is to achieve the basic science understanding that leads to a predictive capability that will be able to tell when and where non-linear internal waves will occur and what effects they will have on the hydrodynamic and acoustic environment. This project focuses on the use of remotely sensed variables, together with models, that can reproduce and predict the generation and structure of these waves, their evolution during propagation, and the processes controlling dissipation.

## **OBJECTIVES**

1). To determine the statistical features of ocean internal waves in SCS. Interpreting ten years of satellite synthetic aperture radar (SAR) images, the statistical features of ocean internal waves in SCS will be determined. The statistical items will include the wavelength distribution, distribution of number of waves in a wave packet, characteristic half width distribution, generation location distribution, occurrence seasonal distribution, and propagation direction spectrum on the continental shelf. The statistical analysis includes the ocean environment conditions and its seasonal variability. The results will provide the users an outline of internal wave behavior in SCS, serve as a basis for empirical prediction of internal wave behavior in SCS, and contribute to creation of a predictive system. 2). To understand the effects of topography/thermocline on the evolution of solitary internal waves in SCS. Sharp changes in bottom topography and thermocline depth are an obvious feature of the SCS continental shelves. Combining satellite images, field observations, and solitary wave dynamics, the effects of those boundary conditions on the evolution of the internal solitons will be examined. The results may be used to predict the behavior of internal waves propagating over the shelf slope. 3). To explore the SAR imaging conversion mechanisms of internal waves. On the basis of the physics of radar imaging of ocean processes, the mechanisms for polarity conversion (bright-dark) of internal waves SAR image will be examined. The results will further reveal SAR imaging mechanisms and be used for SAR image interpretation.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2007</b>		2. REPORT TYPE <b>Annual</b>		3. DATES COVERED <b>00-00-2007 to 00-00-2007</b>	
4. TITLE AND SUBTITLE <b>Satellite Synthetic Aperture Radar Detection Of Ocean Internal Waves In The South China Sea</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>University of Maryland, Department of Atmospheric and Oceanic Science, College Park, MD, 20742</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>code 1 only</b>					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>6</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

## APPROACH

**1) Satellite images and field data.** Satellite SAR is the most powerful sensor for ocean remote sensing because of its all weather, all day abilities, and high spatial resolution. The spatial resolution of the state-of-the-art satellite SAR images reaches 20 – 30 m, and the swath width reaches 100 – 450 km. These specifications match the requirements for observing the ocean internal waves with a spatial characteristic scale within a range from 0.1 km to 10 km. The SAR images used for the project were taken by the ERS-1 and 2, the RADARSAT-1 and 2 satellites. Historical AXBT data will be used to determine the vertical thermal structure in the study area. The data will be obtained from NOAA archives, which are in the public domain.

**2) Data processing methods.** Commercialized image processing software packets will be used for imagery enhancement, orthorectification, filtering, and data extraction.

**3) Theoretical analysis.** The objectives of theoretical analysis are to understand the nature, physics, mechanism, and laws of variation of the studied process, to derive unknown geophysical parameters using parameters and information derived from SAR image interpretation as inputs, to analyze the relation between the studied process and the surrounding environment, and to predict the future development of the studied process.

Dr. Quanan Zheng serves as a lead PI and coordinates the project. Zheng will focus on data collection, satellite image interpretation, and the theoretical analysis. Dr. R. Dwi Susanto from LDEO, Columbia University, serves as a Co-PI. Susanto focuses on image processing, statistical analysis, and takes part in data collection and the theoretical analysis.

## WORK COMPLETED

**1) Analysis of internal wave source sites in the Luzon Strait.** This work aims to locate the source sites in the Luzon Strait for the energetic, long-crest, transbasin IWs observed in the north SCS. The roles of the islands on the eastern side of the strait, Kuroshio, submarine ridges, thermocline depth distribution, and strait configuration played in the IW generation are examined using the cruise data analysis, satellite data interpretation, and dynamical analysis.

**2. SAR observation and dynamical analysis of sub-mesoscale ocean vortex trains in the Luzon Strait** This work uses the Argos satellite-tracked surface drifter trajectory data and ENVISAT (European satellite) ASAR (advanced synthetic aperture radar) images to illustrate the ocean vortex trains (OVT) in the Luzon Strait. Two cases are observed and analyzed. Related dynamical parameters are calculated.

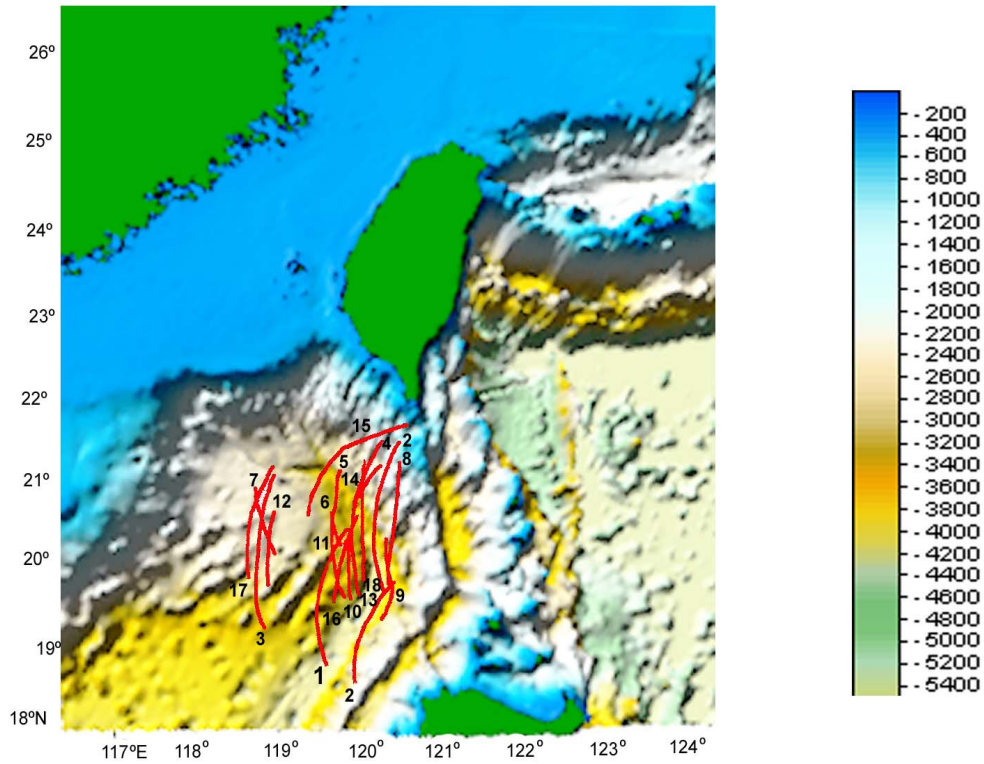
**3) Paper and report preparation.** Based on the data and research results, four papers (see **PUBLICATIONS**) have been prepared and submitted to international-circulated and peer-reviewed journals. One has been published, and another is in press. Three presentations were given in the academic conferences (POSEC 2006, the Fourth International Ocean-Atmosphere Conference, and the NLIWI 2007 meeting), respectively.

## RESULTS

### 1) On generation sources of internal waves in the Luzon Strait

There are two major arguments about the generation sites of IWs in the Luzon Strait. One is the islands on the eastern side of the strait, and another is the Kuroshio west wing [Zheng et al., 2006]. Bole et al. [1994] inferred the generation site as a 4-km-wide channel between Batan Island and Sabtang Island, the southernmost two islands in the Batanes Islands. Ramp et al. [2004] also suggested the Batanes Islands located on the eastern side of Luzon Strait be the generation site of all the largest solitons, and used the site as an coordinate origin for calculating the propagation parameters of IWs in the north SCS. While Yuan et al. [2006] suggested the Kuroshio west wing be an IW disturbance source based on dynamical analysis.

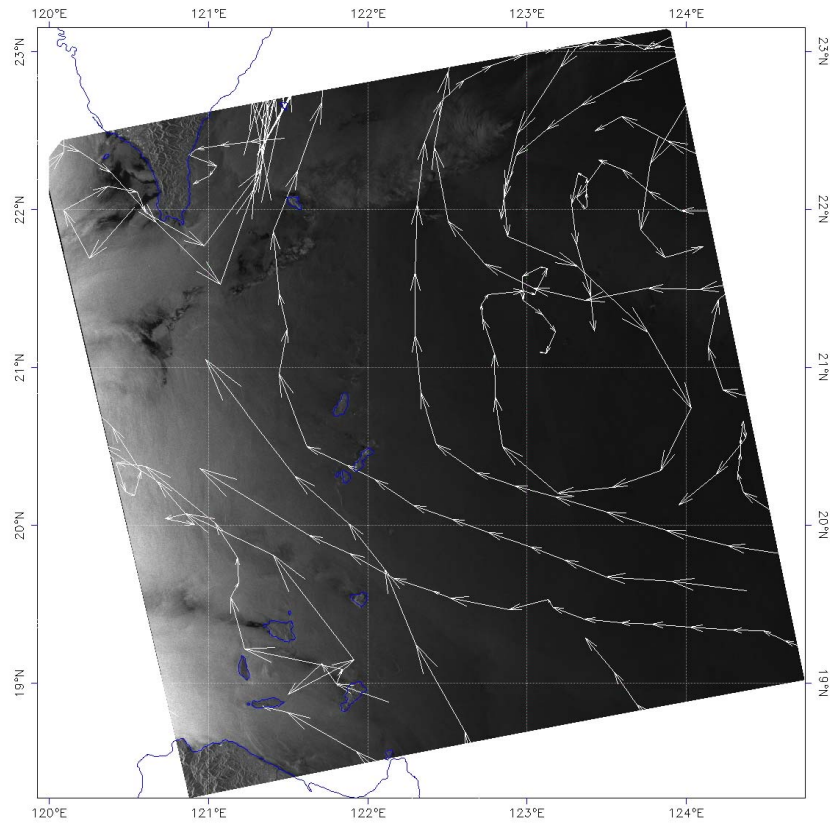
Using the cruise data analysis, satellite data interpretation, and dynamical analysis, the roles of all potential disturbance sources, such as the islands on the eastern side of the strait, Kuroshio, submarine ridges, thermocline depth distribution, and strait configuration played in the IW generation are examined. The islands and channels on the eastern side of the strait are excluded from the list of possible IW source sites owing to their unmatched horizontal dimensions to the scale of IW crest line length, and the relative low Reynolds number [Zheng et al., 2007a]. The possible types of disturbance are the island wakes and vortex trains. The Kuroshio has potential to serve as a radiator for the long-crest IW disturbances, meanwhile, the Kuroshio west (east) wing absorbs the eastward (westward) propagating IW disturbance [Yuan et al., 2006]. Namely, the Kuroshio blockades and plays a role like a “fire wall” for the outside west-east propagating IW disturbances. The 3-D configuration of the Luzon Strait is characterized by a sudden, more than one order widening of the cross section areas at the outlets on both sides, providing a favorable condition for IW type initial disturbance formation. In the Luzon Strait and its vicinity, the thermocline is featured by a westward shoaling all the year around. This asymmetrical distribution of thermocline depth provides the dynamical conditions for the amplitude growth to the westward propagating IW type disturbance, and for the amplitude declination to the eastward propagating one, which will finally be damped. Thus, the west slope of western submarine ridge at the western outlet of the Luzon Strait are the source sites of energetic, long-crest, transbasin IWs in the north SCS. The interpretation results of satellite SAR images during a 13 year period from 1995 to 2007 as shown in Figure 1 provide the excellent evidence for these conclusions.



**Figure 1. The sea floor geomorphology of the Luzon Strait and its vicinity. Red lines represent 18 solitary transbasin IWs observed by satellite SAR from 1995 to 2007.**

## 2) Sub-mesoscale ocean vortex trains in the Luzon Strait

Two cases of ocean vortex trains in the Luzon Strait are observed. The first train of three cyclonic vortices showed up on drifter trajectories from 20° to 20.5°N and from 120° to 121°E, and the second, consisting of five pairs of cyclonic-anticyclonic vortices, occurred on the upstream side of the first one from 19.5° to 20.0°N and from 121.0° to 122.0°E and showed up on the ASAR images acquired on 19 November 2006 as shown in Figure 2. The total length of the vortex train axis reaches about 250 km. All vortices propagate northwestwards ( $\sim 315^\circ$  TN). The mean angular velocity is  $(2.07 \pm 0.18) \times 10^{-5} \text{ s}^{-1}$ . Theoretical models of ocean vortex radar image derived from radar imaging theories are used to extract dynamical parameters from ASAR imagery signatures, which include the distance between two consecutive vortices and that between two rows of vortices of  $(22.6 \pm 1.9) \text{ km}$  and  $(8.2 \pm 1.2) \text{ km}$ , respectively, the maximum rotational velocity radius as 4.70 km, and the vortex rotational angular velocity  $3 \times 10^{-5} \text{ s}^{-1}$ . Dynamical analyses give the mean velocity of the current of  $0.65 \text{ ms}^{-1}$ , and the propagation velocity of the vortex  $0.58 \text{ ms}^{-1}$ . The vortex shedding rate is estimated as  $2.57 \times 10^{-5} \text{ s}^{-1}$ . The Reynolds number is estimated as 50 to 500. For the individual vortex and the vortex train, the Rossby numbers are  $O(0.4)$ , and  $O(0.5)$ , respectively, implying that both vortex and vortex train observed in the Luzon Strait have a sub-mesoscale nature. This study also reveals a strong current with an average surface current velocity of around  $0.7 \text{ ms}^{-1}$  and the direction of around  $315^\circ$  TN flowing directly from the Pacific to SCS passing through the southern Luzon Strait. The mean flow velocity can be calculated using methods developed in this study and OVT dynamical models. This information may provide more insight to the circulation systems in the area including the origin of Kuroshio.



***Figure 2. A composite image of ASAR image with Argos satellite-tracked drifter trajectories of November.***

## **IMPACT/APPLICATIONS**

The results of this project will provide the users a statistical outline of internal wave behavior and boundary conditions in SCS, and will benefit the broader oceanographic community, ocean engineering industries, underwater navigation and operational users. The results may also serve as a basis for empirical, theoretical, and numerical prediction models of internal wave behavior in SCS, and contribute to creation of a predictive system. The results will further reveal SAR imaging mechanisms and be used for SAR image interpretation.

## **RELATED PROJECTS**

The PI of this project serves as a CO-PI for an ongoing ONR PO project titled “Analysis of Fine Structures of Flows, Hydrography, and Fronts in Taiwan Strait”. The study areas of two projects are immediately adjacent. Therefore, two projects sometimes share the same data resources of field observations.

## REFERENCES

- Bole, J. B., C. C. Ebbesmeyer, and R. D. Romea (1994), Soliton currents in the South China Sea: Measurements and theoretical modeling, *Offshore Technology Conference*, Texas, 367-376.
- Ramp, S. R., T. Y. Tang, T. F. Duda, J. F. Lynch, A. K. Liu, C.-S. Chiu, F. L. Bahr, H.-R. Kim, and Y.-J. Yang (2004), Internal tsolitons in the northeastern South China Sea Part I: Sources and deep water propagation, *IEEE J. Oceanic Eng.*, 29, 1157-1181.
- Yuan, Y., Q. Zheng, D. Dai, X. Hu, F. Qiao, and J. Meng (2006), The mechanism of internal waves in the Luzon Strait, *J. Geophys. Res.*, 111, C11S17, doi:10.1029/2005JC003198.
- Zheng, Q., R. D. Susanto, C-R. Ho, Y. T. Song, and Q. Xu, Statistical and dynamical analyses of generation mechanisms of solitary internal waves in the northern South China Sea. *J. Geophys. Res.*, 112, C03021, doi:10.1029/2006JC003551, 2007.
- Zheng, Q., and Y. T. Song, Sub-mesoscale dynamics in the South China Sea: applications of satellite SAR data, *Journal of Ocean university of China*, 2007, submitted.

## PUBLICATIONS

- Zheng, Q., G. Fang, and Y. T. Song. Introduction to special section: Dynamic Processes and Circulation in Yellow Sea, East China Sea, and South China Sea. *J. Geophys. Res.*, 111, C11S01, doi:10.1029/2005JC003261, 2006.
- Zheng, Q., R. D. Susanto, C-R. Ho, Y. T. Song, and Q. Xu, Statistical and dynamical analyses of generation mechanisms of solitary internal waves in the northern South China Sea. *J. Geophys. Res.*, 112, C03021, doi:10.1029/2006JC003551, 2007.
- Zheng, Q., H. Lin, J. Meng, X. Hu, Y. T. Song, Y. Zhang, and C. Li, Sub-mesoscale ocean vortex trains in the Luzon Strait. *J. Geophys. Res.*, in press.
- Zheng, Q., and Y. T. Song, Sub-mesoscale dynamics in the South China Sea: applications of satellite SAR data, *Journal of Ocean university of China*, 2007, submitted.
- Zheng, Q., R. Dwi Susanto, Chung-Ru Ho, Y. Tony Song, and Qing Xu. Satellite SAR observation of solitary internal wave occurrence in the northern South China Sea, PORSEC 2006, November 2-4, 2006, Busan, Korea, 2006.